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PREFABRICATED EXPANDABLE FOAM/WOOD STRUCTURES FOR THEATER OF OP--ETC(U)
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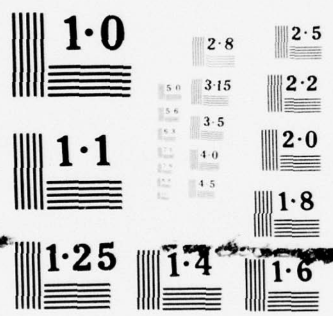

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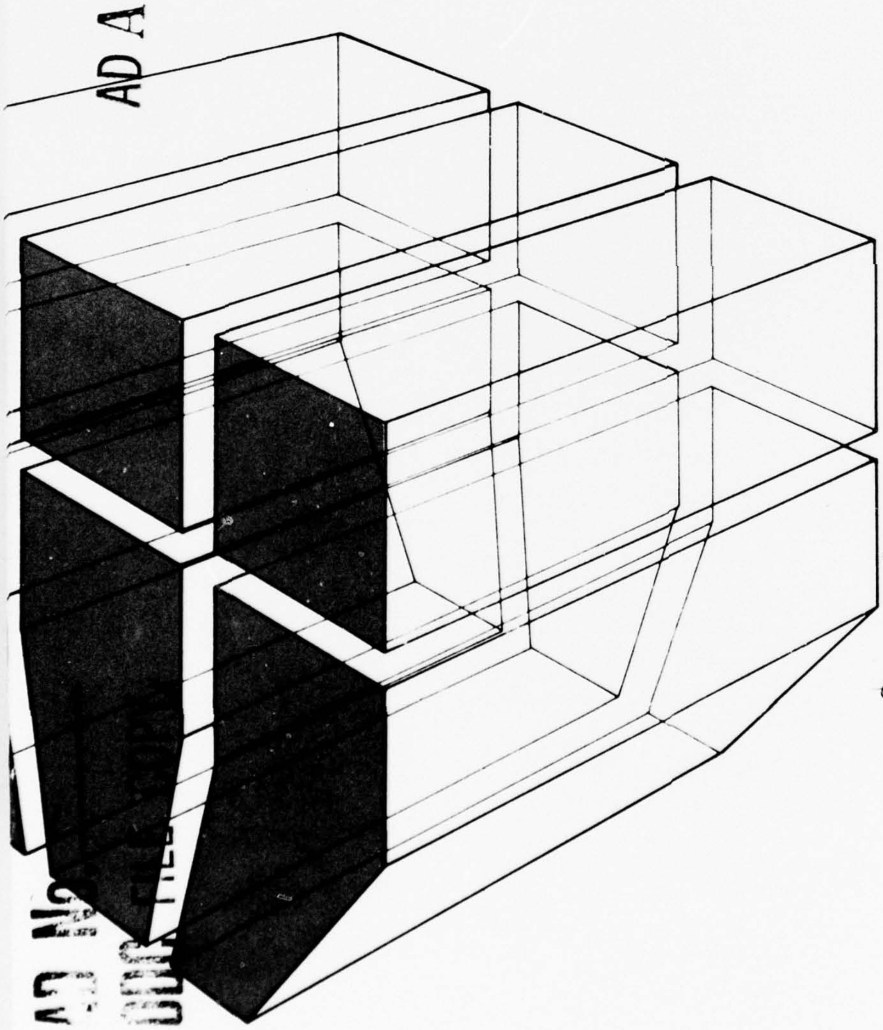
INTERIM REPORT C-45
September 1977
Multi-Purpose Structural Components

PREFABRICATED EXPANDABLE FOAM/WOOD STRUCTURES FOR THEATER OF OPERATIONS



by
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This report, one of a series covering development of multi-purpose structural components,* documents the results of field experiments of several field-fabricated structural components using polyurethane spray-applied foam as a structural and insulative material in combination with wood. The components were evaluated from the standpoints of ease of fabrication, transportability, assembly and erection, relocatability, and expandability. A set of structural components that had potential over

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military application in providing a wide range of temporary facilities for use in the theater of operations was selected.

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*R. L. Trent, T. M. Whiteside, and J. Robertus, *Field Experiment on a Prefabricated Expandable Foam/Wood Structure*, Interim Report C-50/ADA032726 (U.S. Army Construction Engineering Research Laboratory [CERL], 1976); and R. L. Trent, T. M. Whiteside, and J. Robertus, *Erection Procedures for Prefabricated Expandable Foam/Wood Structures*, Interim Report C-52/ADA027382 (CERL, 1976).

FOREWORD

This study was performed for the Directorate of Facilities Engineering, Office of the Chief of Engineers (OCE), under Project 4A763734DT34, "Development of Engineering Support to the Field Army"; Task 04, "Base Development"; Work Unit 003, "Multi-Purpose Structural Components." The applicable QCR number is 1.01.001(4). The OCE Technical Monitor at the time the work documented in this report was performed was Mr. R. Barnard. The current Technical Monitor is Mr. E. McWhite.

The work was performed by the Military and Base Engineering Branch (FOM) of the Facility Operations Division (FO), U.S. Army Construction Engineering Research Laboratory (CERL). The CERL principal investigator at the time the work documented in this report was performed was Mr. R. L. Trent. The current principal investigator is Dr. A. M. Kao. Dr. E. L. Marvin is Chief of FOM and Mr. R. B. Blackmon is Chief of FO.

Appreciation is extended to CAPT J. H. Robertus, USMC, who was assigned to the Department of Engineering Science at the U.S. Army Engineer School during this work, for his assistance in refining the design concepts to reflect theater of operations construction environments and conditions, and to Mr. Harvey Barrett, formerly of CERL, for his assistance and support in the fabrication and structural assembly of experimental components and buildings.

COL J. E. Hays is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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PREFABRICATED EXPANDABLE FOAM/WOOD STRUCTURES FOR THEATER OF OPERATIONS

1 INTRODUCTION

Background

The Corps of Engineers has recognized the need for new and improved construction techniques and materials to support the Army in the field. Increased emphasis is being placed on these areas in response to new and revised tactical scenarios and requirements for more responsive construction support efforts. As part of this effort, the U.S. Army Construction Engineering Research Laboratory (CERL) is conducting research directed at providing construction materials and techniques which can be used by troops in the field to fabricate a major portion of the facilities necessary in the theater of operations (TO), with minimal logistics and training impacts.

Purpose

The major objective of this study is to develop building systems which employ a small number of structural components and can be used to construct a large proportion of the facilities required in the TO. The purpose of the phase of the study documented in this report was to determine the feasibility and cost effectiveness of a set of field-fabricated structural components using spray-in-place polyurethane foam in combination with wood.

Approach

The objectives were achieved by organizing the work program into the following steps:

a. Design criteria development. Building system design criteria were developed based on the specialized environment of the TO (Chapter 2).

b. Building concept development. Several preliminary building concepts using polyurethane foam as a structural material were developed and compared with other potential building system concepts. Evaluation by potential users (the U.S. Army Forces Command and the U.S. Army Training and Doctrine Command) and the U.S. Army Engineer School (USAES) indicated that further investigation of the attributes of foam materials, their structural properties, and fabrication techniques was warranted. Prototype designs were prepared (Chapter 3).

c. Experimental verification of prototype building system. A field experiment was conducted at USAES to verify the feasibility of the selected building system. The results of the experiment were analyzed to provide a basis for improving the system. The modified system was then field tested (Chapter 3). Results of the second field test were then evaluated against the established design criteria (Chapter 4).

d. Comparative computerized evaluations. A computerized building evaluation system--Theater of Operations Building Systems Evaluation Procedures (TOBSEP)[1]-- was used for comparative analyses of the experimental building system against several existing TO building systems (Chapter 5).

Mode of Technology Transfer

The final technology transfer from this study will be through field demonstrations, reports, and Army Training Literature Program (ATLP). The results of this study may also impact on TM 5-301, TM 5-302, and TM 5-303.[2]

2 BUILDING SYSTEM DESIGN CRITERIA

The building system design criteria developed in this study were based on several general requirements recognized at the outset of the study. Ideally, construction of the building systems should not require any special tools or impose extensive training requirements on Corps field personnel. The prefabrication procedures, material systems, and methods of production should provide the military planners and Corps field commanders with the ability to rapidly mobilize a broad production base. The building systems and implementation methods should also enable the military planner to adjust the design details of the structural components to make maximum use of available materials and stock.

The following subsections present the major criteria developed in this study for acceptability of proposed building systems designed for application in the TO.

---

[1] T. C. Ryan and L. C. Tietz, *Evaluation System for Proposed Theater of Operations Structures*, Technical Report C-14/Vols I (ADA006014), II (ADA006495), and III (ADA006145) (U.S. Army Construction Engineering Research Laboratory [CERL], 1975).

[2] *Army Facilities Components System-Planning*, TM 5-301; *Army Facilities Components System-Designs*, TM 5-302; *Army Facilities Components System-Logistic Data and Bills of Materials*, TM 5-303 (Department of the Army, 1973).

Logistic Requirements

a. Speed of construction. New building concepts should increase productivity of engineer troop units and enable them to build more facilities faster, while reducing manpower requirements.

b. Weight/cube ratio. Weight/cube ratio is a major consideration in movement of construction materials, both in terms of shipment from CONUS to the appropriate TO and transshipment to and from proposed construction and prefabrication areas of depots within that theater.

c. Durable packaging. Durable packaging must be provided to prevent damage, deterioration, and losses due to other factors.

d. Transportability. The systems should be easy to transport to and within the TO, in the context of current scenarios.

e. Handling properties of structural components. The components must be capable of being handled by engineer troops without large materiel-handling equipment.

f. Ease of repair. Any components damaged during transshipment must be capable of being repaired so they can be used without materially affecting the quality of the completed facility or its fulfillment of its intended purpose.

Material Availability

Required materials should be manufactured commercially within the Continental United States (CONUS) in large quantities by numbers of reputable potential suppliers.

Tool and Training Requirements

Special tool and equipment requirements must be maintained at minimal levels; specialized equipment represents a long-term problem in terms of the overall objective of decreasing present tooling inventories.

Auxiliary support equipment requirements must also be minimized.

Training requirements of CE personnel should ideally be covered by present military occupational specialties (MOS), with minimum impact on specialized skills.

Expandability and Flexibility

Facilities should be capable of being modified to provide additional space or to meet different operational functions. For example, a

20-person barracks should be readily modifiable to handle 80 people instead of 20, or an administration center should be capable of being modified to serve as a dispensary or radio-communications center.

Phased Construction

The system's economical life should be capable of extension through the use of new materials and components; cost-effective modification of temporary facilities to more permanent and longer-life facilities should be possible.

Relocatability

Some relocations may be required to reduce the overall building costs in the TO.

Economy - Initial and Operating Costs

Conserving manpower and materials is essential, as is accomplishing construction with a minimum of shipped-in tonnage and volume. Maintenance and operating costs should be minimized.

3 CONCEPT DEVELOPMENT AND EXPERIMENTAL VERIFICATION

Concept Development

Initial efforts were concerned with acquiring background information, supported by both laboratory and field testing, on the structural properties of foam and foam/wood complementary components and structures, the optimum balance between the proportion of foam and wood used in such components, the structural integrity of buildings erected and assembled from such components, and the ability of Corps field personnel to use the basic expanded-foam-spray processing technique under field conditions.

Two basic structural configurations were considered: a cylindrical structure with hemispherical roof and a rectangular structure with pitched roof. A cylindrical system was constructed at CERL for evaluation (Figure 1). The test indicated that the system was too static to allow flexible space enclosure; the system could be expanded in only one direction. Additionally, adhesive connections between components limited their relocatability. Finally, the building's light weight and low mass required hold-down devices to resist wind loading. This system was hence eliminated from further consideration. Emphasis was then placed on developing a building system using the conventional rectangular shape with pitched roof configuration. Two field experiments were conducted to support the development work.

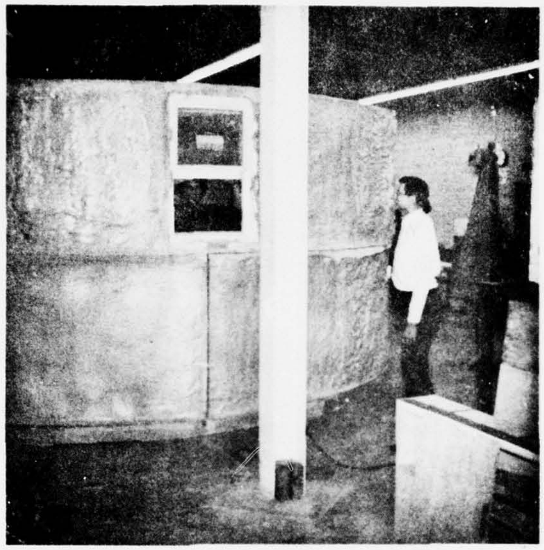

Figure 1. Cylindrical foam building system.

Field Experiment at USAES

Inherent bonding characteristics between expanded foam and other materials such as wood were used in fabricating the structural components. The roof and walls were constructed of 4 by 8 ft (1.2 by 2.4 m) panels fabricated with 1 by 4 in. (2.5 by 10 cm) lumber and foam. Nails were used to connect the panels. Figure 2 shows the wall panels being erected and Figure 3 shows the completed building. The structure's relatively light weight necessitated use of cables to tie down the building to resist wind loading.

Polyisocyanurate foam was used in the field experiment, rather than the polyurethane foam previously tested at CERL, because of its superior flame-retardant properties. This decision was based on information from manufacturers and suppliers that indicated that the two materials would have similar physical properties.

The field experiment was held at USAES, Fort Belvoir, VA, between 19 October and 1 November 1974. The results of the field experiment indicated the following:

a. A set of field-fabricated components using foam/wood components can be manufactured and assembled in the TO by Corps personnel to provide temporary building facilities.

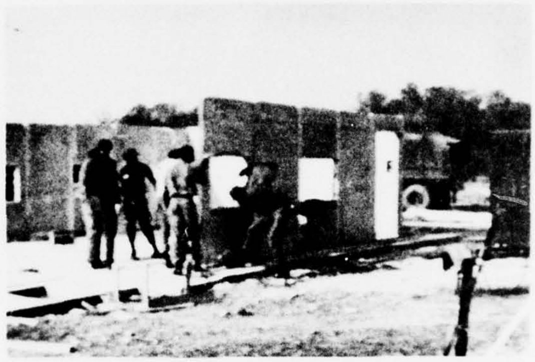

Figure 2. A panelized foam building under erection at USAES.

Figure 3. Completed foam building at USAES.

b. Corps personnel with a minimum of on-the-job training can successfully use spray-foam equipment to fabricate the structural components.

c. The structural design was capable of withstanding wind-loading and weathering action for 6 months. It was determined, however, that the component design, which was based on minimum usage of wood, was subject to racking and strains due to the wind loading. This resulted in formation of separation cracks at the junctions of the components and between foam and wood members.

d. The polyisocyanurate foam did not possess structural properties equivalent to those of polyurethane foam, particularly in terms of adhesion to the wood members incorporated in the components, and in terms of contraction coefficients while cooling to ambient temperatures during the curing process. These two properties resulted in the formation of separation cracks between the foam and wood members, thus substantially weakening the structural components and necessitating that excessive secondary work be performed following initial panel fabrication. Although an additional layer of foam applied over cracks following erection temporarily solved this problem, it detracted from the building's appearance.

e. Site and climatic conditions hindered panel fabrication somewhat. Panels were sprayed outdoors following construction of the wood framework at another site. The combination of low temperatures (30 to 40°F [-1 to 40°C]), movement of the framework, and an insufficiently rigid base over which to spray the panels resulted in field-fabrication difficulties.

f. The integral floor/foundation system that was used was impractical. Floor panels were fabricated to be placed over a level, graveled site. This required considerable site preparation and permitted excessive movement of the building during construction.

g. Use of cables to withstand wind-loading effects should be avoided because of the cost and the effect on the structure. The cost of the cables and the manpower required to install them was the largest single expense incurred during the field experiment. While the cables enabled the structure to withstand wind loading, the localized stresses imposed on the connections between the components where the cables were attached to the structure resulted in further crack formation.

h. Evaluation of the condition of the components after being disassembled and shipped to CERL indicated that approximately 80 percent of the components could be reclaimed and repaired for reuse (Figure 4). It is believed that this percentage could be substantially improved by using polyurethane foam rather than the polisocyanurate mixture used in this experiment.

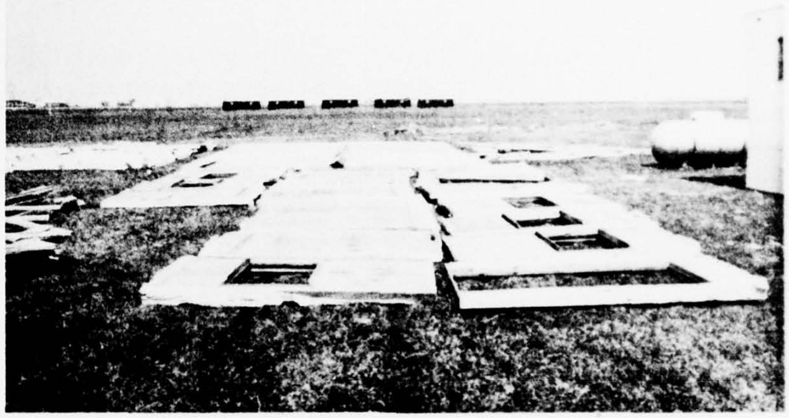

Figure 4. Disassembled/foam building components shipped to CERL for evaluation.

Field Experiment at CERL

Revised Structural Concept

The results of the USAES field experiment were used in developing a revised structural concept for field testing at CERL. To provide a vehicle for evaluating composite foam/wood components, it was determined that the foundation, floor, wall, and roof systems should be fabricated from two to four different components having designs based on various ideas. The most successful of these components would be selected for the optimal building system.

The various components would be fabricated in a controlled environment. Panels would be fabricated and sprayed in one covered location to control the quality of the finished product.

To eliminate the need for cable tie-downs against wind loading, plywood sheet and 2 by 4 in. (5 by 10 cm) lumber would be used to fabricate roof and wall panels. The plywood sheets would provide rigid connections between the walls and the roof and floor structures. In addition, the plywood would carry the lateral load induced by the wind.

Description of Experimental Building Erected at CERL

A 24 x 32 ft (7.32 x 9.75 m) building was designed and erected. The building used two foundation systems, two floor panel designs, four wall panel designs, two truss systems, and two roof panel designs. The

amount of foam in each component type was varied to evaluate the foam's impact on panel strength, rigidity, and handling characteristics. The component modular dimensions were based on 4 x 8 ft (1.22 x 2.44 m) plywood sheets. Figures 5 and 6 show the building elevations and sections. The completed building is shown in Figure 7. The methods and techniques used in the experimental building are listed below.

a. Foundation system. The alternative techniques investigated included "bents," and laminated posts and girders for transferring building loads to the ground. A bent is a long-span beam supported at both ends by posts and rigid connections. The bent was fabricated as a wood "I" beam with a 3/4-in. (1.91-cm) thick plywood web and 2 x 4 in. (5 x 10 cm) lumber flanges. The laminated-girder and post design consisted of built-up 2 x 6 in. (5 x 15 cm) lumber supported at the ends and middle of the span. The "bent" and laminated-girder designs are shown in Figures 8 and 9, respectively. Figures 10 and 11 show the completed foundation systems.

b. Floor system. All floor panels were prefabricated from full sheets of plywood and 2 x 4 in. (5 x 10 cm) joists. Floor panels used in conjunction with bents were made of 1/2-in. (1.27-cm) plywood with joists spaced at 16 in. (0.41 m). The panels, which were designed to be simply dropped into place, were attached to the protruding plywood web of the bent. Floor panels over the laminated girder were fabricated from 3/4 in. (1.91 cm) plywood with joists at 24 in. (0.61 m). These panels were attached by a size 60d spike driven through the panel into the girder. Half of each of the floor panel types were furnished with spray-applied foam whose thickness tapered from approximately 3 in. (7.62 cm) along the edge of the 2 by 4 in. (5 by 10 cm) lumber to approximately 1 1/2 in. (3.8 cm) between the joists.

c. Wall panel systems. The following types of wall panels were fabricated and installed in the buildings:

1. 4 by 8 ft (1.22 by 2.44 m) panels faced with 3/8-in. (0.95-cm) plywood without foam.

2. 8 by 8 ft (2.44 by 2.44 m) and 8 by 12 ft (2.44 by 3.66 m) panels faced with 1/4-in. (0.64-cm) plywood. A layer of foam, approximately 2 in. (5.08 cm) thick at the edges and 1 in. to 1 1/2 in. (2.54 to 3.81 cm) thick in the middle of the panels was applied during panel fabrication.

3. Double-faced 4 by 8 ft (1.22 by 2.44 m) panels using 1/4-in. (0.64-cm) plywood, foam-filled using a pouring technique rather than spray application methods.

4. 4 by 8 ft (1.22 by 2.44 m) panels having edges of 2 by 4 in. (5 by 10 cm) lumber filled completely with spray-applied foam without plywood; the exterior was faced with waterproof paper.

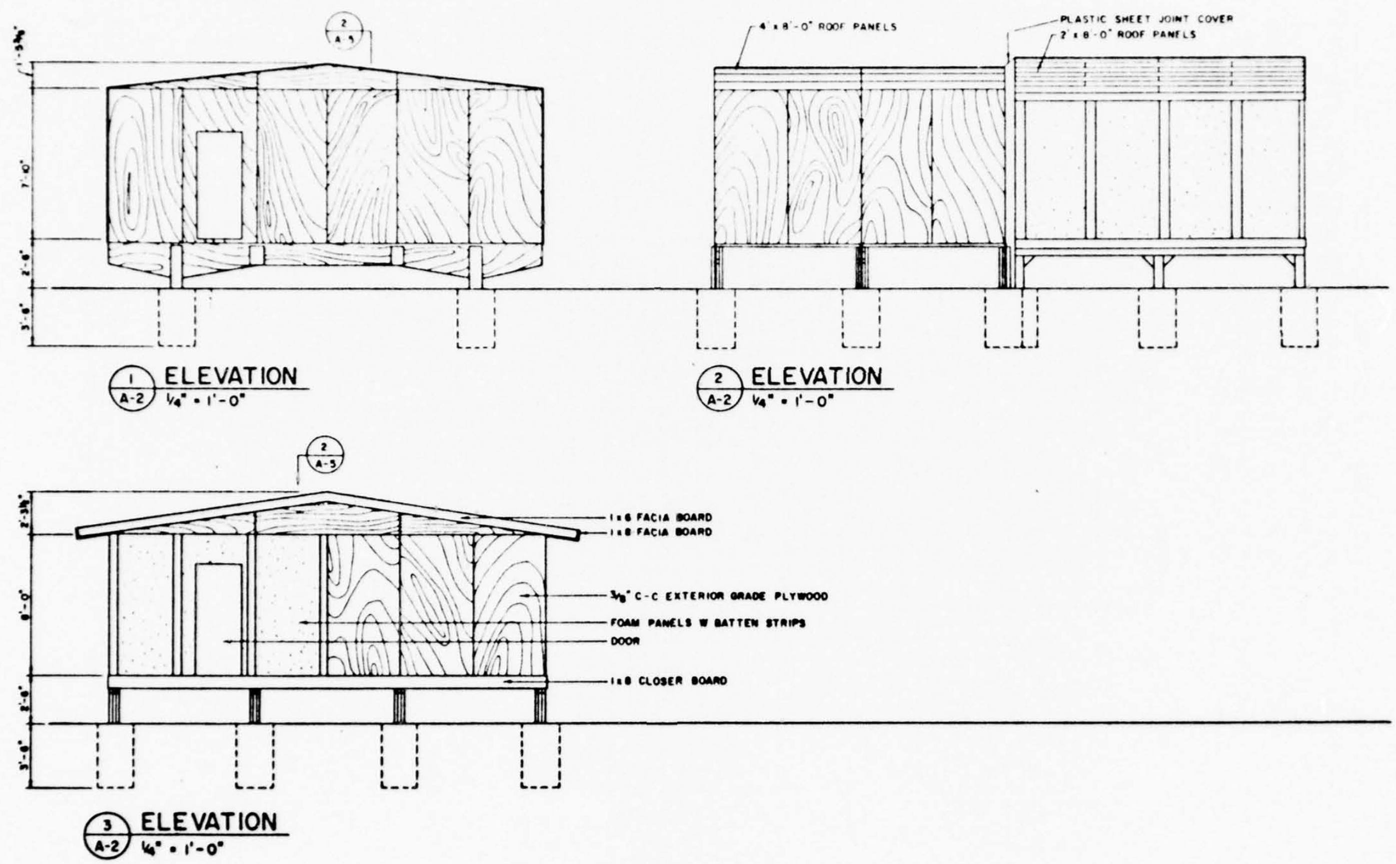

Figure 5. Elevation views of CERL structure. SI conversion factors: 1 ft = 0.3048 m; 1 in. = 25.4 mm.

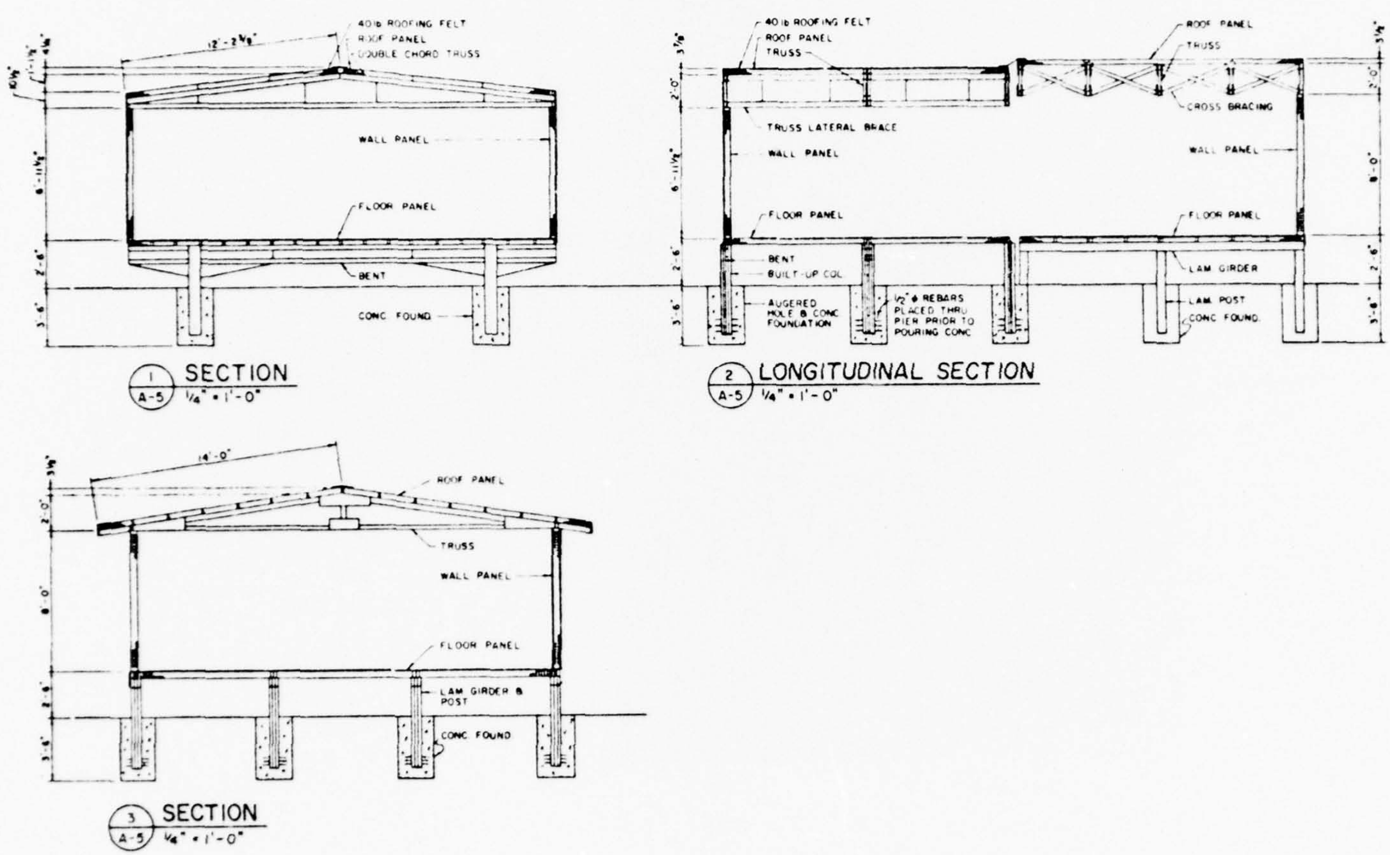

Figure 6. Sectional view of CERL structure. SI conversion factors: 1 ft = 0.3048 m; 1 in. = 25.4 mm.

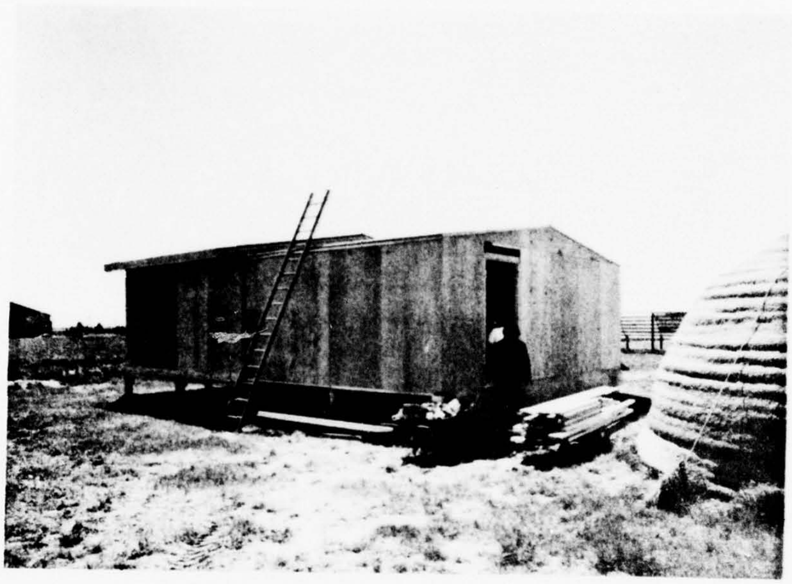

Figure 7. Completed CERL foam/wood experimental building.

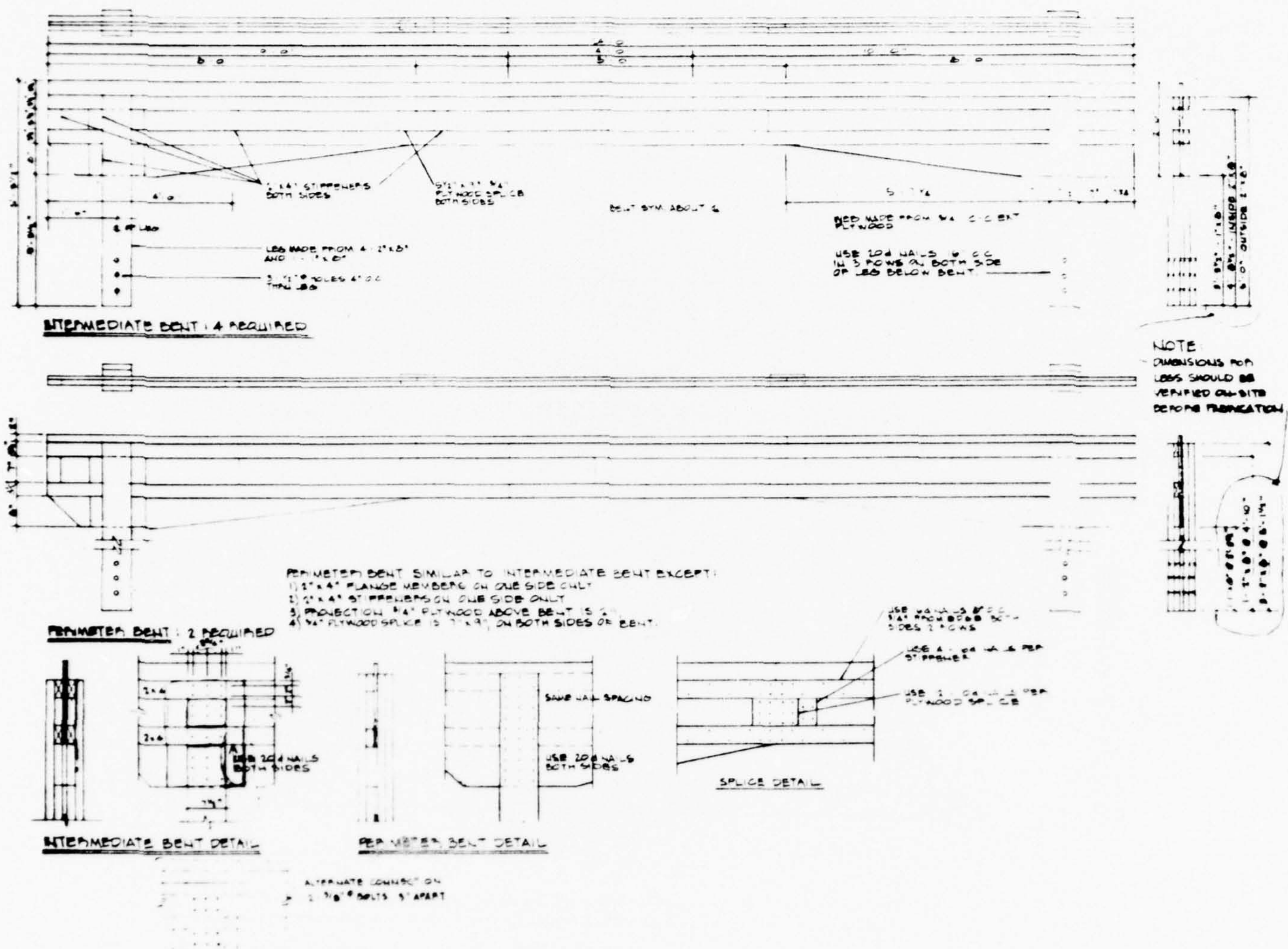

Figure 8. Foundation "bent" design for CERL building. SI conversion factors: 1 ft = 0.3048 m; 1 in. = 25.4 mm.

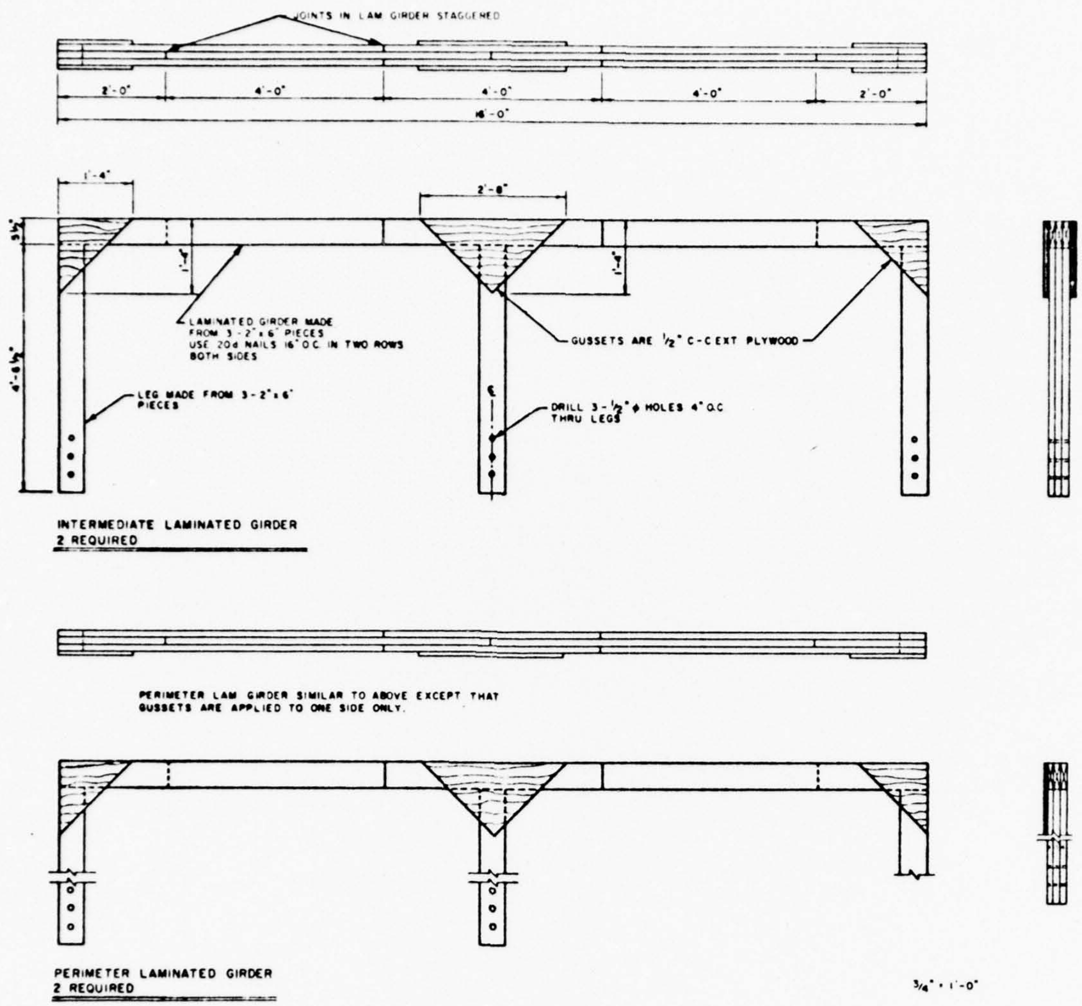

Figure 9. Foundation "laminated-girder" design. SI conversion factors: 1 ft = 0.3048 m; 1 in. = 25.4 mm.

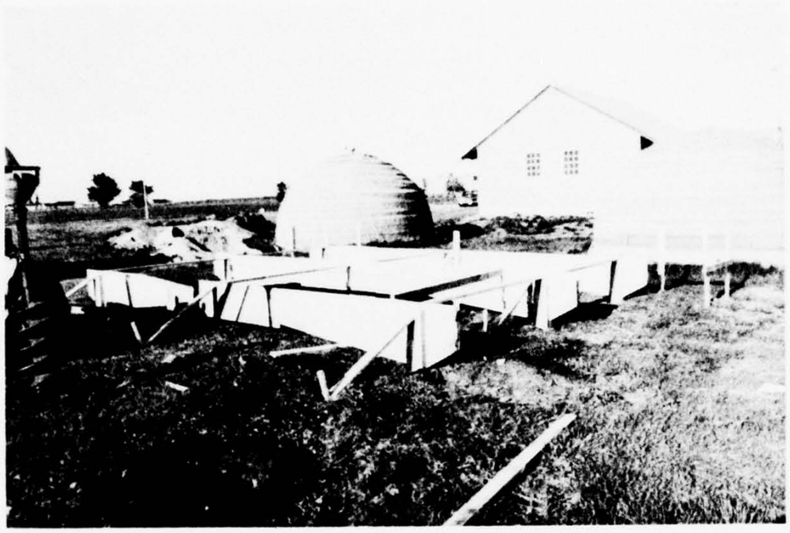

Figure 10. Completed foundation bents.

Figure 11. Completed laminated-girder foundation system.

d. Roof panel systems. The following types of roof panels were fabricated and installed in the buildings:

1. 4 by 8 ft (1.22 by 2.44 m) panels, with 2 by 4 in. (5 by 10 cm) rafters on 24-in. (0.61-m) centers, faced with 1/2-in. (1.27-cm) plywood; foam was applied on interior surfaces during fabrication, approximately 2 in. (5.08 cm) thick at rafters and 1 to 1 1/2 in. (2.54 to 3.81 cm) thick between rafters.

2. 4 by 8 ft (1.22 by 2.44 m) panels, with 2 by 4 in. (5 by 10 cm) rafters on 16 in. (0.41 m) centers, faced with 1/2-in. (1.27-cm) plywood and no foam.

e. Truss systems. Two types of wood trusses were fabricated and erected. A slope of 1.75/12 (approximately 8.3 degrees) was used for the pitch of both roofs.

1. Double-chord truss. This truss was designed to be placed on 8-ft (2.44-m) centers similar to the foundation system. It is similar to the bent concept, because plywood gussets were placed beside the 2 by 4 in. (5 by 10 cm) double chords and protruded for attachment to the roof panels.

2. King post truss. This was a conventional truss fabricated of 2 by 4 in. (5 by 10 cm) lumber. The trusses were placed on 4-ft (1.22-m) centers.

Evaluation and Selection of Most Effective Components

The features incorporated in the structure were evaluated from the standpoints of ease of fabrication in the field or within CONUS, transportability to and within the TO, assembly and erection to form structures, and relocatability and expansion within the TO. Based on this evaluation, the optimal set of components was selected.

a. Foundation system. The bent system is considered optimal because it possesses the following advantages over the post and laminated girder system:

1. Only two ground connections (augered hole, and concrete or earth-filled) are required per bent. These connections are accessible from the exterior of the building. Systems based on the post and laminated-girder system required twice as many ground connections and their interior supports were not easily accessible for pouring concrete from the exterior of the building.

2. Bents can be fabricated using more commonly available 2 by 4 in. (5 by 10 cm) lumber and 3/4-in. (1.91-cm) plywood sheets.

3. Leveling and adjustment of the bent and floor systems can be accomplished after the system is constructed prior to pouring concrete around the posts. This is done by shoving up the bents during the floor system construction.

b. Floor system. The optimal floor system uses 1/2-in. (1.27-cm), 4 by 8 ft (1.22 by 2.44 m) plywood panels, with 2 by 4 in. (5 by 10 cm) floor joists, spaced on 16-in. (0.41-m) centers. The bottom surfaces of the panels are filled with spray-applied foam, approximately 3 in. (7.62 cm) thick surrounding the 2 by 4 in. (5 by 10 cm) joists, and 1 1/2 in. (3.81 cm) thick between the floor beams. This design was chosen because of the additional rigidity and insulation provided by the foam.

c. Wall panel system. The optimal wall panel system uses 1/4-in. (0.64-cm) single-faced 8 by 8 ft (2.44 by 2.44 m) panels, with spray-applied foam on the interior surfaces. This system was chosen because (1) the foam provides sufficient rigidity to enable transportation within the TO without damage; (2) 8 by 8 ft (2.44 by 2.44 m) lightweight panels can be easily handled by engineer troops during erection; and (3) fabricating one 8 by 8 ft (2.44 by 2.44 m) panel is easier than fabricating two 4 by 8 ft (1.22 by 2.44 m) panels. In addition to serving as the principal cladding material, the plywood wall panel also acts as the primary connection between foundation, floor, and roof components.

d. Roof panel system. The optimal 4 by 8 ft (1.22 by 2.44 m) roof panels use 1/2-in. (1.27-cm) plywood with 2 by 4 in. (5 by 10 cm) rafters spaced on 24-in. (0.61-m) centers with spray-applied foam on the interior surface for rigidity and insulation. This system was chosen because the individual roof panels are designed to be dropped onto the trusses and nailed to protruding plywood nailers. The protruding plywood nailers insure proper alignment of the panels.

e. Truss system. The double-chord truss was judged to be superior because (1) fabrication time was not excessive compared to that of the king post truss; (2) erection was speeded due to the 8-ft (2.44-m) spacing, which resulted in fewer connections; and (3) these trusses would be able to better withstand handling during transportation within the TO. Material requirements for both truss systems were approximately equal.

Cost-Effectiveness of CERL Experimental Building

The material costs for the CERL experimental building were less than $2,000. The structure was prefabricated in approximately 160 man-hours, and erected by three men in 2 1/2 days, requiring a total effort of 60 man-hours. Based on a rate of $3/hour for troop labor cost, the total cost of the experimental building was calculated to be $2,660, or $3.46/sq ft ($37.24/m²).

4 EVALUATION OF COMPLEMENTARY FOAM/WOOD STRUCTURAL CONCEPT

The results of the CERL field experiment were analyzed and compared to the design criteria outlined in Chapter 2 of this report.

Logistics Requirements

a. Speed of construction. Use of prefabrication techniques greatly reduced the time required for erection of the building at the construction site; the overall manpower effort was also reduced due to increased working efficiency.

b. Weight/cube ratio. A reduction of 30 to 50 percent in weight/cube ratio of materials transported to the TO can be realized, depending on the AFCS building system chosen for the comparison.

c. Durable packaging. Packaging the lumber required for TO construction of the system is the same as for comparable AFCS buildings. Foam materials are contained in 50-gal (0.19-m^3) metal drums.

d. Transportability. The materials required for the system can be transported to and within the TO by normally available containerized methods.

e. Handling properties of structural components. Components can be easily handled by 2 to 3 people after fabrication and during erection.

f. Ease of repair. Components used in building can be easily repaired during handling/erection procedures.

Material Availability

The lumber required is standard, dimensioned, commercially available plywood and 2 x 4 in. (5 x 10 cm) lumber. Foam materials are available from many commercial sources in large quantities within CONUS. Appendix A discusses the properties of polyurethane foams and foaming. Foam material inventory in the TO could be readily maintained, since containerization is in metal drum form.

Tool and Training Requirements

Special equipment requirements are limited to polyurethane spray-foam application gun equipment which is commercially available. Appendix B provides information on the foam-spraying equipment. Field experience indicated that engineer troops can operate the equipment and apply the foam materials with limited training.

Expandability and Flexibility

Structures erected from the components may be expanded to increase internal floor area to satisfy an expanded functional requirement, or may be upgraded to meet different functional requirements. The structures can be adapted for several types of facilities, such as bachelor officer's quarters, administration buildings, communication facilities, and hospitals.

The wall and roof panels in the experimental structure are fabricated with 1/4-in. (0.64-cm) and 1/2-in. (1.27-cm) plywood sheets, respectively, with 1 to 1 1/2 in. (2.54 to 3.81 cm) of foam. The combination can be varied as necessary. For instance, if other thicknesses of plywood are available, such as 1/4 or 3/4 in. (0.64 or 1.91 cm), the proportion of foam used in the panels can be adjusted to provide the necessary strength and insulative qualities.

Phased Construction

The complementary foam/wood structure was developed to meet a 3- to 5-year design life and does not particularly lend itself to phased construction.

Relocatability

The design provides for interconnections between structural components using scaffolding (shoulder-headed) nails; this permits disassembly and up to three (estimated) relocations. With the present design, the only unreclaimable elements would be the connection ties between the bents and concreted ground connections.

Economy - Initial and Operating Costs

The unit cost of the CERL foam/wood experimental building system, including material and labor, is approximately \$3.46/sq ft (\$37.24/m^2) compared to approximately \$5/sq ft (\$54/m^2) for comparable existing AFCS alternatives. Low material wastage is attained by using full 4 by 8 ft (1.22 by 2.44 m) plywood sheets for panel construction. In addition, polyurethane foam's superior insulative qualities will reduce heating and air conditioning load appreciably, if these utilities are required. The operating costs of heating and cooling should be reduced by one-third to one-half those of more conventional TO structures. Using field-fabrication techniques results in significant overall labor savings. Erection of the building using prefabricated components is accomplished much more quickly and with considerably less effort than is required for conventional site construction.

5 COMPARATIVE COMPUTERIZED EVALUATION

A 24 by 96 ft (7.32 by 29.26 m) facility was designed using the optimal components selected in Chapter 4. This facility was evaluated and compared to other prefabricated, relocatable systems using the TOBSEP program. The evaluation numbers determined by TOBSEP and the cost figures indicate that the CERL experimental foam/wood panel system is competitive with other prefabricated, relocatable systems that have been evaluated.

6 CONCLUSIONS

Based on the results of the field experiments, the following conclusions can be drawn:

a. Field prefabrication and on-site assembly of structural components using plywood and dimensional lumber is a viable method of providing cost-effective building facilities in the theater of operations.

b. The fabrication techniques required to manufacture the structural components and the methods of erecting the facilities are within the MOS skill levels possessed by engineer units.

c. The spray-in-place expanded foam technique and equipment can be used in the TO to fabricate the wood/foam panels with limited training for engineer troops. However, a sheltered prefabrication area is necessary to produce satisfactory wood/foam composite structural components. Wood panels without foam insulation, foundation bents, and roof trusses can be constructed in the open.

d. The modular design based on use of full 4 by 8 ft (1.22 by 2.44 m) sheets of plywood and dimensional lumber results in minimum material wastage and simplifies field erection of components.

APPENDIX A:

POLYURETHANE FOAMS AND FOAM SYSTEMS

Formation

Polyurethane foams result from a set of carefully controlled chemical reactions and physical phenomena. This section describes the materials and reactions used in forming polyurethane foams.

"Polyurethane" refers to a family of polymers based on the reaction of an isocyanate group with some other reactive group, particularly the hydroxyl group. The resulting polymer is not a foam; it may be in any form from a soft, flexible rubber to a hard, glassy material. Polyurethane foams are formed by generating a gas within the polymer as polymerization reactions occur. The gas forms bubbles which are entrapped until the polymer is completely formed, resulting in a cellular structure.

The gases generated in a foam polyurethane mixture arise from (1) reaction of a calculated amount of water with an equivalent excess of isocyanate (above that required for the polymer) proceeding through several steps and ultimately producing carbon dioxide gas or, (2) including in the mixture a predetermined amount of a low boiling point liquid such as a halocarbon (Freon), which is volatized by the heat from the exothermic polymerization reactions, thus creating a gas which is trapped in the polymer mass.

The constituents of a typical polyurethane foam mixture include:

a. Isocyanate. The isocyanate group consists of $R - N = C = O$, in which the single bond from the N is attached to a larger molecule R. In order for polymer chain growth to occur, two or more isocyanate groups must be attached to each larger molecule.

b. Polyol. Often referred to as the "resin," it consists of $R' - OH$ groups attached to a larger molecule R'. As with the isocyanate, it is necessary for two or more OH groups to be attached to the same molecule for the polymer molecule to grow to great length.

c. A foaming agent--either water or halocarbon as previously described.

d. A cell control agent or surfactant is usually required to modify the viscosity and/or surface tension of the mixture to insure that gases formed are trapped and retained and that the bubbles will generally be of the same size. Certain detergents and silicone oils are used widely as surfactants.

e. Catalysts are used to regulate the start and the rates of reactions leading to the polyurethane polymer. Often two or more catalysts are required to achieve the desired results. When water is included in the formulation to cause foaming, a catalyst favoring a water-isocyanate reaction is required.

f. Flame retardants of phosphate character, antimony oxide, chlorine, or bromine are frequently used to reduce the foam's ease of ignition or rate of burning. They will not, however, prevent burning of the foam in a sustained fire. The high surface-to-volume ratios of foams tend to increase flammability problems.

When the materials listed above are mixed in the proper proportions, reactions typified by

isocyanate polyol

$$\sim R - N = C = O + HOR'\sim$$

$$\begin{array}{l} \qquad\quad H \quad OR'\sim \\ \qquad\quad / \quad\ / \\ \sim R - N - C = O \end{array}$$

urethane group

occur. Formation of many such groups results in a polymer network. The average chain-to-chain connection (crosslink density) and the average distance between urethane groups gives the final polymer its rigidity properties.

The amount of gas formed determines the density of the foam; density may be varied from about 1.5 to 50 lb/cu ft (24 to 980 kg/m^3).

Physical Properties

The foam's physical properties depend on rigidity and density. Commercial foam systems are normally preblended into two materials--isocyanate and resin blend (polyol, surfactant, blowing agent and catalyst) designed to give 2 lb/cu ft (32 kg/m^3) density foams. This combination yields foams that have the typical properties listed in Table A1.

These values in Table A1 can be used for estimating purposes. Since these properties are considered typical, however, a particular foam system should be specifically evaluated for a particular application.

Table A1

Typical Properties of Commercial Foam Systems

Density, lb/cu ft (kg/m^3)	2.0 (32)
Compressive Strength (10% strain), psi (kPa)	35 (241)
Compressive Modules, psi (kPa)	1000 (6895)
Tensile Strength, psi (kPa)	38 (262)
Shear Strength, psi (kPa)	25 (172)
Shear Modulus, psi (kPa)	400 (2758)
K Factor (insulation). Btu/hr/sq ft/F/in. (W/m·K)	.12 Btu (0.02)
Water Absorption, lb/sq ft (kg/m^2)	0.033 (0.161)
Maximum Service Temperature, °F (°C)	200 - 250 (93 - 121)
Coefficient of Linear Expansion, in./in./°F (mm/mm/°C)	6×10^{-5} (1.1×10^{-4})

Higher density foams are generally stronger structurally but have poorer insulating qualities.

Cost

In general, commercial foam systems for 2 lb/cu ft (32 kg/m^3) foam cost between \$.60 and \$.70/lb (\$1.32 and \$1.54/kg). Special formulations may cost more, and a premium is usually added for small quantity orders. Since the isocyanate and resin are derived from petroleum or natural gas, the price may vary accordingly.

Shelf Life

The effective shelf life of a foam system depends largely upon two things--storage conditions and catalyst deterioration. Storage conditions will shorten the shelf life if the materials are stored at either extreme of the optimum storage temperature range--50° to 90°F (11° to 32°C). More critical is the deterioration of the catalyst in the resin blend. If long storage is anticipated, the catalyst should not be

blended in until ready for use, and the entire resin blend should be agitated and stirred thoroughly.

Most commercial formulations are guaranteed for at least 6 months in original unopened containers. Many foam systems are dependable for much longer than that--in some cases up to 3 or 4 years.

Sources

There are numerous producers of polyurethane foam systems in the United States.

APPENDIX B:

POLYURETHANE FOAM MIXING EQUIPMENT

Generating a good quality foam requires that the foam system components be properly mixed in the proper proportions. Improperly mixed foams may appear to be good but not be stable over a long period of time, or they may not possess the desired strength or insulative qualities.

Numerous manufacturers of paint-spraying equipment have made and sold foam-spraying equipment. Foam-spraying equipment, however, is considerably more complex and requires better maintenance than does paint-spraying equipment. Since isocyanates react with moisture in the air, the equipment must be cleaned after each spray period.

Basically, a foam-spraying machine must do several things: (1) it must accurately and dependably deliver the foam material components in the proper proportions; (2) it must provide adequate mixing to assure near homogeneity of the blend, and (3) it must be manageable by an operator; i.e., the operator must be able to spray the mixed material without excessive difficulty.

Both portable and "stationary" units are commercially available. Most models can accommodate up to 150 ft (45 m) of spray hose. Additional features may be incorporated into the machine design. Heaters may be provided to raise the material temperature. Hoses may also be heated and/or insulated. Some circumstances (spraying foam in cold weather) may make such features necessities rather than optional items.

Figure B1 shows a typical foam sprayer in schematic form (also see Figure 13). Table B1 provides a partial list of companies which market equipment and can provide information concerning operation, cost, and maintenance. Most sprayers require compressed air at the rate of about 15 cfm (0.42 m^3/minute) at 100 psi (689 kPa) pressure and 220 V, single-phase electrical power.

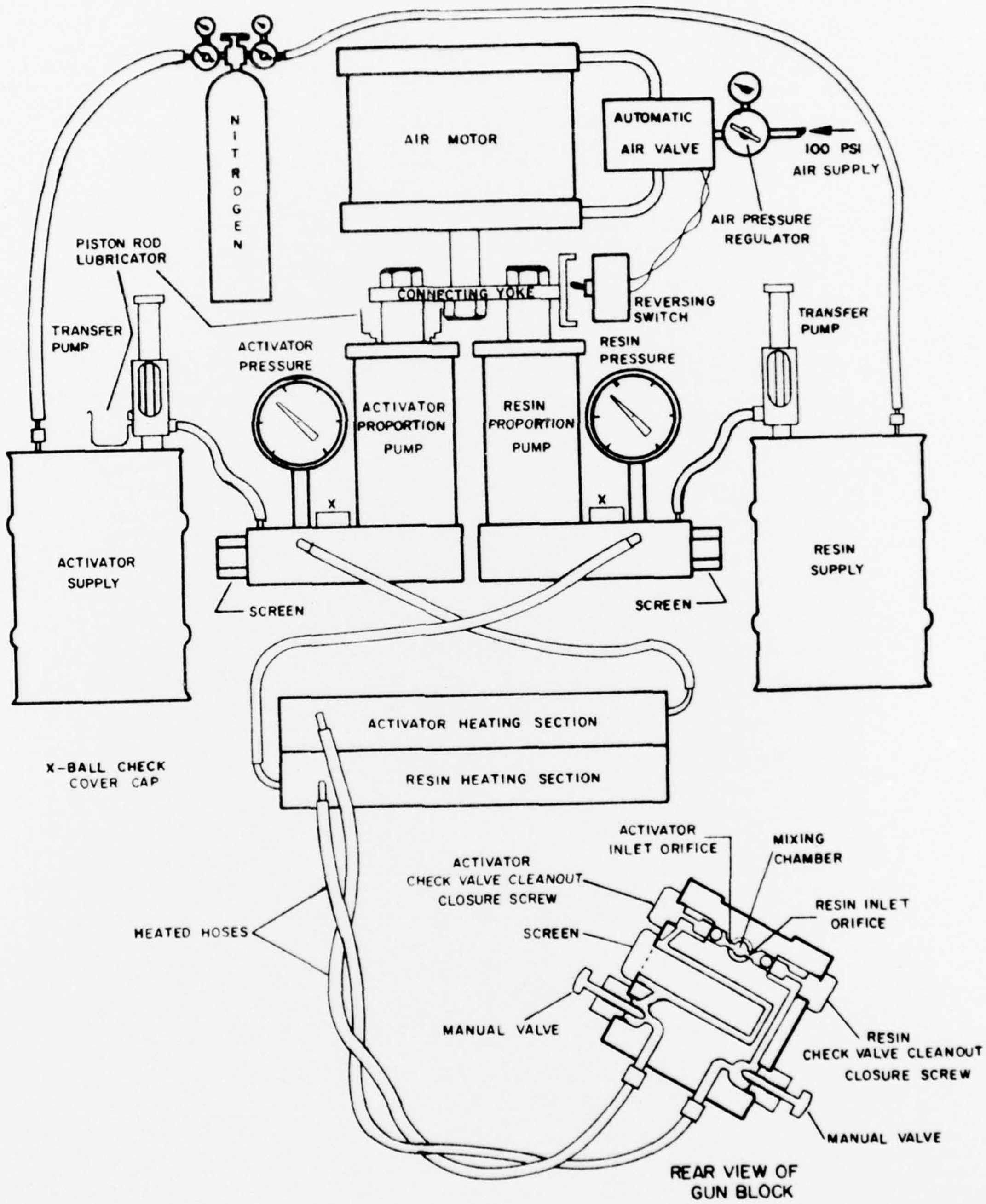

Figure B1. Basic component schematic (spray equipment). This model is manufactured by Gusmer Corporation.

Table B1

Partial List of Foam Spray Equipment Manufacturers

Accuratio Systems, Inc.
1472 South Floyd St
Louisville, KY 40208

Admiral Equipment Division
Upjohn Co.
305 West North St
Akron, OH 44303

Binks Manufacturing Co.
Plastic & Resin Equipment Division
9201 West Belmont Ave
Franklin Park, IL 60131

Ransburg Corporation
3939 West 56th St
Indianapolis, IN 46208

Graco, Inc.
60 Eleventh Ave, NE
Minneapolis, MN 55441

Gusmer Corp.
P.O. Box 164
414 Rt. 18 Spring Valley Rd
Old Bridge, NJ 08857

North American Urethanes, Inc.
Keytum Engineering Division
1717 Boettler Rd
Uniontown, OH 44685

The Martin Sweets Co., Inc.
3131 W. Market St
Louisville, KY 40212

Venus Products, Inc.
1862 Ives Ave
Kent, WA 98301

While foam spraying is relatively straightforward, operators should be trained in the proper use and maintenance of the equipment. Normally, a 1-week course can provide all necessary training in setup, operation, troubleshooting, and maintenance procedures.

Maintaining a ready supply of repair and/or replacement parts is advisable to avoid downtime in case of a malfunction. Experienced manufacturers are aware of the more common high-mortality parts and can suggest a basic stockage list. They also usually offer quick response to orders for repair parts. Proper training will provide the operator with enough knowledge to replace parts as needed.

The industrial/commercial users of spray foam equipment recommend purchasing and maintaining the simplest piece of equipment capable of doing the desired job. Options on the machine can often cause problems in handling, operation, and maintenance. In addition, these options may represent a substantial increase in the original cost of the equipment.

Spray foam equipment usually costs from $3000 to $10,000, depending on the volume capability and the extra items included.

Foam production capability ranges from about 2 to about 20 lb/minute (0.9 to 9.1 kg/minute). Larger outputs are possible, but may cause problems, in that the operator may not be able to move about fast enough to make full use of the output. For example, a 20 lb/minute (9.1 kg/minute) machine can produce 10 cu ft (0.28 m^3) of 2 lb/cu ft (32 kg/m^3) foam per minute. If a 1-in. (25-mm) layer is being applied, the 10 cu ft (0.28 m^3) would cover an area of about 60 sq ft/minute (5.6 m^3/minute) of operation. Area coverage at this rate would obviously require frequent movement. A good, practical output is about 8 to 10 lb/minute (3.6 to 4.5 kg/minute), representing 25 to 30 sq ft/minute (2.3 to 2.8 m^2/minute) of coverage.

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